Renewable and Sustainable Energy Reviews 21 (2013) 89–101

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Life cycle assessment of 50 MW wind firms and strategies for impact reduction

A. Rashedi [a], I. Sridhar [a,*], K.J. Tseng [b]

[a] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore
[b] School of Electrical and Electronics Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

ARTICLE INFO

Article history:
Received 6 September 2012
Received in revised form
7 December 2012
Accepted 9 December 2012
Available online 26 January 2013

Keywords:
Wind energy
Onshore wind turbine
Offshore wind turbine
Life cycle analysis
Material selection
Inventory improvement

ABSTRACT

The world today is continuously striving toward a carbon neutral clean energy technology. Hence, renewable wind power systems are increasingly receiving the attention of mankind. Energy production with structurally more promising and economically more competitive design is no more the sole criterion while installing new megawatt (MW) range of turbines. Rather important life cycle analysis (LCA) issues like climate change, ozone layer depletion, effect on surrounding environments e.g. eco-system quality, natural resources and human health emerge as dominant factors from green energy point of view. Hence, the study covers life cycle impact analysis (LCIA) of three wind farms: one onshore horizontal, one offshore horizontal, another vertical axis. It appears that vertical axis wind farm generates per unit electricity with lowest impact followed by horizontal offshore and horizontal onshore farms. The study, henceforward, discovers most adverse impact contributing materials in today's multi megawatt wind turbines and subsequently substitutes copper, the topmost impact contributor, with more eco-friendly aluminum alloys and its corresponding process routes. In this process, it reduces overall life cycle impacts up to 30% for future greener wind farms. In later stages, it compares all major electricity production technologies, viz., oil, diesel, coal, natural gas, wind, solar, biomass, nuclear, hydro plant in a common platform which demonstrates the wind farms performing the best except the hydro-kinetic ones. However, as the study suggests, offshore VAWT farm may even perform better than hydro-kinetic farms because of higher capacity factors in the high sea. Findings from the study can be deployed to harness massive scale green electricity from environmentally more clean and green turbines.

Contents

* Corresponding author. Tel.: +65 67904784; fax: +65 67924062.
E-mail addresses: amma0002@ntu.edu.sg (A. Rashedi), msridhar@ntu.edu.sg (I. Sridhar), ekjtseng@ntu.edu.sg (K.J. Tseng).

1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2012.12.045

Nomenclature

C_m	material cost per kg
ρ_{elr}	electrical resistivity
kPt	kilo ecopoint
tkm	transportation of 1 t goods over 1 km
personkm	movement of 1 person over 1 km
A/E	acidification/eutrophication
C	carcinogen
CC	climate change
DALY	disability adjusted life years
E	ecotoxicity
EQ	ecosystem quality
FF	fossil fuels
HH	human health
LU	land use
M	minerals
OL	ozone layer depletion
PDF	potentially disappeared fraction
PDF $\times$ m^2 $\times$ yr	1 PDF $\times$ m^2 $\times$ yr indicates disappearance of all species from a 1 m^2 area for 1 year
R	radiation
Re	resources
RO	respiratory organics
RI	respiratory inorganics

1. Introduction

World's fossil fuel reserves that once accelerated the drive to modern civilization and powered its industries are now been marked as predominant green house gas emitters and environmental contaminators in earth's atmosphere. These grim realities provide huge impetus for embarking on an alternative energy platform with clean and green outlook [1–4]. As being one of the most ubiquitous, in-exhaustible and sustainable energy on planet earth, the wind power plays a consequential role in this concourse [1,4]. Wind power is relatively cheaper than solar power. Solar power is not financially viable due to high commissioning cost; specially in high latitudes ($>40^\circ$ north or $>40^\circ$ south) it will be long time for solar power to achieve the parity with existing fossil fuel based plants whereas wind power can be commercially installed in any part of the world with wind speeds around 8 m/s or more. European countries like Denmark has already envisaged a plan to meet almost 50% of its electricity demand from wind power by 2025 [4]. In the end of year 2011, the global wind power installed capacity increased to 240 GW which is a massive 220% increase in just a time span of last 5 years. Along with onshore wind farms, offshore and floating turbines are also quickly penetrating the energy market. By October 2010, 3.16 GW of electricity started reaching the national grids from offshore wind plants which is expected to rise to 16 GW by 2014 and to 75 GW by 2020 [5]. Northern European countries are leading offshore wind power generation race with 53 farms installed by the end of 2011. Floating offshore wind turbine concept has also been materialized very recently. Hywind 2.3 MW, the world's first large-scale deep-water floating turbine, is generating electricity for the Norwegian grid since its inception in September 2009 in the North Sea. The turbine cost was US$62 million to build and deploy and it is expected to generate about 9 GWh of electricity annually [5]. In turn, vertical axis wind turbine system offers smaller weight, simpler foundation and less maintenance cost, however, its power co-efficient is still to match with horizontal axis wind turbine. As worldwide electricity demand is doubling itself in every 10 years and commercial scale wind farm development has expanded over 80 countries, it is of absolute importance to evaluate the wind technologies according to environmental perspective [4] apart from economics. To this implication, an overall life cycle inventory (LCI) and life cycle impact assessment (LCIA) of existing horizontal and vertical wind farms are explored in this paper. Besides determining the inventory and emission aspects of only the operation phase, life cycle inventory and impact assessment study performs a cradle to grave investigation of entire stand-in technology [28]. Guidelines of such LCI and LCIA analyses are epitomized by industry wide well-reckoned standardization bodies. Out of these, LCA guidelines of International Standard Organization (ISO) cover life cycle documentations extending from LCA principle and framework to goal, scope definition, inventory analysis, life cycle assessment and its interpretation [6,7]. Based on these guidelines, the study evaluates existing wind farm LCA study and, henceforward, redesigns it for a better carbon neutral, greener environment.

Worldwide only a few researchers have, so far, explored LCA studies for onshore and offshore turbines. Ardente et al. [8] have studied the energy performance and life cycle assessment of a horizontal axis onshore wind farm under solid waste, air and water emission categories using environmental product declaration (EPD) methodology. This study revealed the manufacturing phase to be the largest environmental impact contributor to the wind turbine. Weinzettel et al. [9] have evaluated the life cycle impact of a conceptual floating offshore wind turbine by CML 2 baseline 2000 V2.03 method. Here they compared the floating turbine concept with another offshore one where the life cycle impacts appear to be equivalent for both turbines. Fleck and Huot [10] have evaluated the environmental impact and life cycle cost of a small wind turbine for residential off-grid use. While comparing to a diesel generator system, the 0.4 kW wind turbine system offers almost 93% green house gas emission reduction. A 2 MW Gamesa onshore wind turbine with 80 m rotor blade installed in a Spanish wind farm has been the focus of Martinez et al.'s LCA study [11]. Here 95% material weight is considered for the life cycle inventory to calculate the impact with accompanying sensitivity analysis. However, these farms have never been compared in any article at sub-assembly level. Also how different primary, secondary and tertiary manufacturing processes contribute to overall LCA impact is left untouched. In addition, it is of utmost importance to identify how each and every engineering material contributes to overall wind turbine life cycle impact; this can eventually pave the way to substitute the existing materials with environment friendly ones. Conversely, life cycle analysis of vertical axis wind technology is entirely in its infancy. There is no referred work published in this domain, as prominent citation databases affirm. Reason behind this endures in non-existency of major scale commercial basis vertical axis wind farm as compared to the horizontal ones. This paper considers all these issues as potential areas of LCA study and compares the LCA impacts of three 50 MW wind farms based on SimaPro software [12]: one of which comprises of onshore horizontal axis wind turbine, another consists of offshore horizontal axis wind turbine and the last one incorporates onshore vertical axis wind turbine. For simplicity, these turbines will be represented as HAWT onshore, HAWT offshore and VAWT, respectively in the remaining text.

2. Model design

2.1. Life cycle assessment goal and scope

The first goal of the study is to evaluate three 50 MW wind farms in terms of their impacts. Next, the study achieves to sort out different materials in terms of their life cycle eco-profile. Based on the same, it proposes new material and, thus, obtains green turbines with lower life cycle impact. The study, accordingly, focuses on 10 REpower 5M turbine, both for HAWT onshore and offshore farms. With rated output of 5 MW and rotor diameter of 126 m, it is currently one of the largest wind turbine and, so far, it is successfully been commissioned in number of onshore and offshore locations. Turbines of same rated power and same technology are selected to enhance the comparisons between onshore and offshore technologies. Though rotor and nacelle components of both turbines are almost same, site-specific differences exist in tower, foundation and balance of system components. Next, for vertical axis turbine, Sandia's on-grid, two-bladed Darrieus turbine is chosen. Due to lower energy conversion efficiency, dynamic instability problems, fatigue and catastrophic failure issues, there are only a few vertical axis wind turbine manufacturers in the world, and, all of them have the commercial designs with rated power in the range of kilowatt. Hence, getting reliable LCI data for a larger scale vertical axis wind turbine is much more challenging in comparison to horizontal axis wind turbine. However, Sandia's VAWT design has been in smooth operation for a long time and its inventory data is available in public domain. The Darrieus turbine offers lesser weight, lower blade load and simpler foundation than horizontal axis one. However, how the Sandia machine competes environmentally with the horizontal ones is the focus of current study. The present 1.6 MW Sandia machine is also one of the largest in its category with 45.72 m rotor diameter, 68.58 m tower height and 5.18 m ground clearance [14]. The electricity generation from all these horizontal and vertical turbines have been quantified and it amounts to 148.92, 223.38, and 109.07 GWh/year with an equivalent capacity factor of 34% (HAWT onshore), 51% (HAWT offshore) and 24.9% (VAWT), respectively [12–14].

2.2. Life cycle assessment methodology

The overall LCA study is performed based on ISO standard 14040 and 14044 [6,7]. The outcome of LCA study generally depends on various factors such as life cycle process under consideration, inventory allocation, impact assessment method, evaluation step and functional unit—to name a few. A schematic overview of the life cycle processes is highlighted in Fig. 1. To ensure conservativeness in the analysis, neither reuse nor recycling is considered in the study. Also necessity of inventory allocation does not come into the picture as wind farms produces nothing except electricity.

The Eco-indicator 99 impact assessment method is used for the study [16] which carries three different methods of LCA evaluations based on model uncertainties. Out of these, egalitarian perspective includes extremely long term and even lightly proven effects while individualist perspective deals with only short term and robustly proven facts. Hierarchist perspective, in turn, deals with moderate time perspective and substances are only included if there is scientific consensus regarding their effect. The ongoing study performs life cycle analysis based on hierarchist methodology.

Eco-indicator 99 calculates life cycle impact based on 11 categories that incorporate carcinogens (C), respiratory organics (RO), respiratory inorganics (RI), climate change (CC), radiation (R), ozone layer depletion (OL), ecotoxicity (E), acidification/

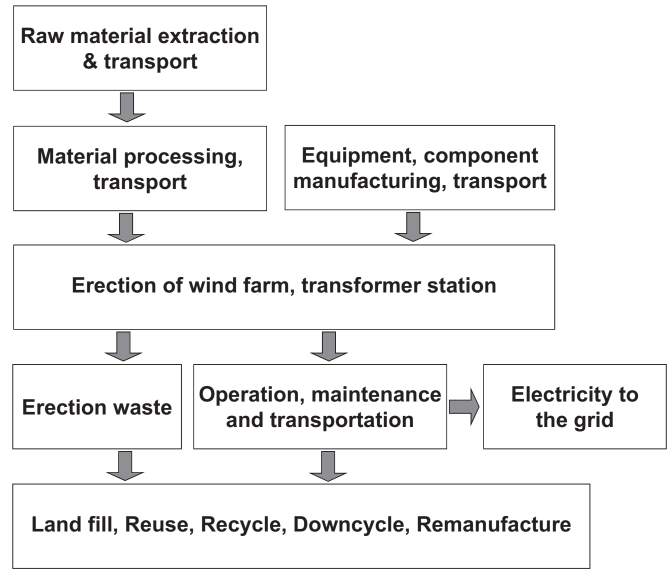

Fig. 1. LCA processes of wind farms.

eutrophication (A/E), land use (LU), minerals (M) and fossil fuels (FF). Out of these, CC, OL, C, RO, RI and R have the same unit DALY (Disability Adjusted Life Years) and, accordingly, they are categorized within a damage category 'human health' (HH) [16]. DALY measures the weighted average disability caused by different types of diseases. A damage value of 1 DALY indicates the decrease of 1 year life for one average individual.

Other two impact categories, viz., FF and M constitute another damage category 'resources' (Re) in unit MJ/kg of extracted material. Here a damage value of 1 represents an additional MJ/kg of energy needed in further extraction of the same due to lower remaining reserve. Another damage category 'ecosystem quality' (EQ) incorporates the impact categories like LU, A/E and E; this measures the change in ecosystem in the unit 'potentially disappeared fraction' (PDF) of plant species $PDF \times m^2 \times yr$. A damage of 1 $PDF \times m^2 \times yr$ means all species will disappear from a 1 m^2 area for 1 year.

For inter-farm comparisons, rated power generation (50 MW) and unit electricity generation (1 kWh) are used as functional unit (FU) while for process scale life cycle, 1 kg mass unit is used for comparison. Industry standard wind turbine life-time of 20 years is assumed for all farms.

2.3. Life cycle inventory of HAWT onshore and offshore farm

Inventory data relating to HAWT onshore and offshore turbines are mostly agglomerated from REpower website and other supplier sources [12,13,15,17–23]. A few other data regarding materials, resources and consumables are collected from prevalent statistical sources and manufacturing datasheets [24–26]. Relevant life cycle inventory (LCI) databases are used for process definition. Few assumptions are made in conjunction that seems to be in agreement with overall farm scale. Up-scaling is opted in few cases based on past researches [8]. It is, nevertheless, difficult to gather all necessary suppliers' information about full particulars of the turbines. Hence, the focus is implied here to collect data, at least, for all well-known components. Specially, for numerous electrical, mechanical and electronic components of nacelle, the material weights are assumed of somewhat higher value to nullify the impact of unknown manufacturing and life cycle processes that are yet to be acknowledged in 20 years long project life time.

REpower 5M total blade weight stands at almost 54 t (see Table 1). Each blade is 61.5 m long and weighs 17.74 t and is made of composite prepreg material [22]. It is assumed to contain 70% glass fiber and 30% epoxy resin. Due to necessary cut-off during pre-pregging, actual fiber weight will be more. Hence, fiber weight is scaled up by 10%. The 18 m long nacelle weight stands at 315 t [19]. In addition to manufacturing of various nacelle components, final finishing e.g. welding, metal cutting and subsequent assembly processes are accomplished at turbine erection stage. Turbine main shaft and bed frame are dominantly made of steel and cast iron. Gearbox set is predominantly made of steel and cast iron. Equivalent steel and cast iron processes are selected for steel and cast iron from Ecoinvent database material according to average European Union (EU) based plant conditions [27]. Generator and transformer are modeled according to the environmental product declaration data of the manufacturer. Generator mainly consists of steel and copper with minor percentage of other materials [24]. Transformer primarily consists of steel, copper and some amount of aluminum, porcelain [25].

Tower is mainly manufactured of steel [19]. With regard to painting purposes, the 'alkyd paint, white, 60% in H_2O, at plant' option of Ecoinvent database is selected [27]. HAWT onshore turbines are erected on concrete foundations [19]. As like Elbehafen port onshore REpower 5M installation condition, the foundation of the wind farm is assumed to consist of 1300 m^3 concrete and 180 t steel [18].

HAWT offshore plant, in turn, is presumed to be installed in 30 m deep sea-water located around 30 km from the shore. Unlike the onshore foundation, jacket type sub-structure together with legs, bracings and piles is used here to support the tower. Eight piles, each one with 50 m length and 1.07 m diameter, together combine to 315 t. Jacket frame, sleeves and transition

Table 1
Life cycle inventory of wind farms [8,12–15,17–27,29].

Sub-assembly and process	Material with corresponding process	Unit	HAWT onshore	HAWT offshore	VAWT
Rotor	Steel	ton	710	710	
	Glass fiber	ton	420	420	
	Epoxy	ton	162	162	
	Aluminum	ton			858.8205
Nacelle (in case of VAWT it includes drive and power train components)	Steel	ton	2047.5	2047.5	1030.448
	Lubricating oil	ton	630	630	630
	Cast iron	ton	472.5	472.5	
	Copper	ton	189	189	
	Aluminum	ton	106.15	106.15	
	Lead	ton	94.5	94.5	
	Epoxy resin	ton	59.85	59.85	
	PVC	ton	47	47	
	PET	ton	39	39	
	Glass fiber	ton	31.5	31.5	
	ABS	ton	9.5	9.5	
	Ceramic tiles	ton	6.3	6.3	
	Silica sand	ton	3.15	3.15	
	Tap water	l	1,000,000	1,000,000	1,000,000
	Brass	ton			1.474172
	Rubber	ton			0.637864
Tower	Steel	ton	3450.6	2000	1478.839
	Alkyd paint	ton	20	20	
	Aluminum	ton		3.75	
Foundation	Concrete	m3	13,000		
	Steel	ton	1800	8220	658.8429
	Alkyd paint	ton		23	
	Aluminum	ton		7	
Ancillary	Aluminum	ton	37	44.05	37
	Brick	ton	14		14
	Cement	ton	10		10
	Copper	ton	12.2	33.1	12.2
	Gravel	ton	22		22
	HDPE	ton	5.2		5.2
	Polybutadiene	ton	24.1	19.26	24.1
	PVC	ton	28	28.52	28
	Steel	ton	2	830	2
	Alkyd paint	ton		6	
	Glass fiber	ton		1.2	
	Transformer oil	ton		48	
	Kraft paper	ton		1.5	
Additional life cycle processes	Diesel	MJ	18,050	22,050	18,050
	Electricity, medium voltage	MWh	1700	2650	2300
	Transport, barge tanker	tkm	30,000	146,000	30,000
	Transport, freight, rail	tkm	5000	5000	5000
	Transport, lorry 16-32t	tkm	8200	8200	8200
	Transport, lorry 3.5-16t	tkm	2000		2000
	Transport, passenger car	personkm	22,000	1000	22,000
	Welding, arc, steel	km	23.5	39.5	11.9
	Wire drawing, copper	kg	13,000	93,000	

node weighs around 425 t whereas other secondary structures like boat landings, J-tubes, anodes weigh 85 t. Together, the full structure weighs 825 t [20,21].

Onshore wind farm needs maintenance equipment storage area and proper extension of existing roads and highways as these are usually installed in remote places. The building works depend on steel, brick, concrete and road works need gravel, cement, coal tar, etc. Road connection between the farm and the city is necessary for maintenance purpose. The onshore turbines are connected to the existing national distribution grid by a 10/60 kV transformer station; this transformer station is not included in the study. Total, there is 10 km of 10 kV cables for connecting 10 turbines to the existing transformer station. These cable lines carry substantial weight. Relevant data regarding the manufacturing of cables is up-scaled from the previous study of an Italian wind turbine [8].

In offshore plant, a high voltage transformer is modeled to increase the transmission electricity voltage. The transformer settles in a platform made of pile and jacket sub-structure. The jacket legs are interconnected by lattice girders and bracings. Each of the 6 piles is 50 m in length and 1 m in diameter. As well, they carry total weight of 235 t. In addition, there is a steel boat landing platform for maintenance activities. Together with jacket frame and boat platform, whole transformer platform weighs 575 t [20]. On top of the transformer platform, a steel structure is assembled to house the high voltage transformer. Data of this transformer is collected from manufacturer's datasheet [25].

The steel structure is assumed to be installed onshore and transported to the offshore plant as a single module. The module is placed upon the transformer platform by means of a floating crane. Cathodic protection system is opted for rust and corrosion prevention while aluminum is allocated as active anode material. Paint repair and renewal activities become essential once in a time span of 10 years, so the inventory is updated accordingly. Other than this, 34 km long offshore cable is estimated in the study. This cable is modeled based on the data provided by Norwegian input–output table [26].

Besides manufacturing of components, wind farm erection phases require transportation, assembly and other construction works. Transportation to plant site includes transportation by light goods vehicle, lorry, rail freight and sea freight. The 'tkm' is used as transportation unit which indicates transportation of 1 t goods over 1 km. In addition, turbine erection and foundation construction activities require fuel (diesel) and medium voltage electricity. Welding and metal cutting activities also need to be performed sequentially.

In turn, operation and maintenance phase activities include routine inspection, paint, repair, renewal activities and change of lubrication (turbine rotating parts usually go through high level of wear and tear). A technician must carry out inspection of 10 turbines and cables four times a year; for that 22,000 personkm passenger car transport is included in the model for the overall plant life of 20 years. Another 2000 tkm transportation by 3.5–16 t lorry is allocated for maintenance related freight. Conversely, HAWT offshore farm will be inspected eight times per annum. Regular inspection of the offshore cable is assumed to be insignificant. Additional dismantling and land-filling activities will be carried out by trucks and light goods vehicle at onshore and by sea vessel at offshore location.

2.4. Life cycle inventory of VAWT farm

For vertical axis machine, the key material and process data are congregated from corresponding Sandia National Laboratories documentations [14,29] (see Table 1). VAWT turbine is built on

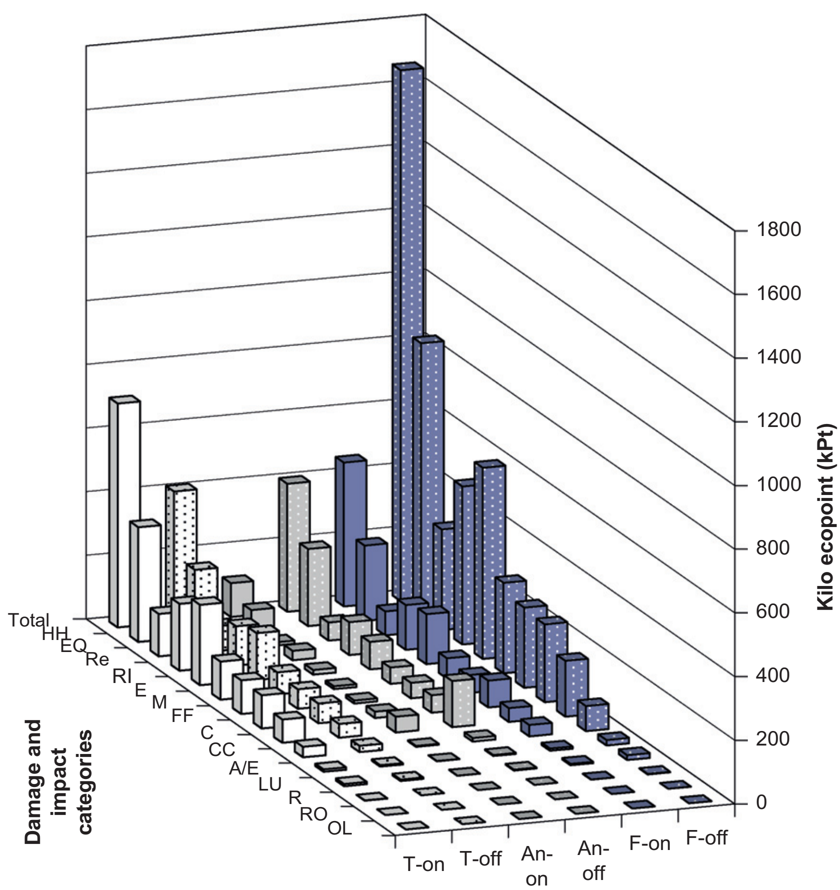

Fig. 2. LCA assessment of tower (T), ancillary parts (An), foundation (F) sub-assemblies of horizontal axis turbine: on-onshore, off-offshore turbine (FU = 50 MW).

two aluminum extruded, uniform thickness blade that are rigidly attached to a central tower. Contrary to HAWT, Darrieus turbine does not annex any well-defined nacelle. Nevertheless, all of the major power train components, e.g., shaft, gear, generator, transformer and disc brake system are available in VAWT. The Sandia machine possesses one vertical, low speed and another horizontal, high speed shaft through an enclosed gearbox. The power train components are predominantly made on steel with a small percentage of brass, synthetic rubber, etc.

A large diameter, thin-wall steel tube tower transmits torque from blades to the revolving shaft. The full structure is supported by three guy cables attached to the top of the VAWT and by anchorage at ground level. Cable bridge strand manufactured of steel material is chosen for guy cable to maintain structural rigidity. Ancillary cable data is assumed likewise HAWT study. Roads and establishment works have been ensured as well.

During operation phase, lubrication oil is necessary to reduce wear and tear and for smooth, tranquil operation of machine parts. The components are lubricated, accordingly, once in every 6 months. Additionally, guy-cable tension and lubrication leaks will be inspected twice in a year. Other life cycle processes, e.g., transportation by lorry, rail and sea-freight, consumption of medium voltage electricity, steel arc welding, burning of diesel fuel during erection phase activities are modeled likewise onshore farm. The landfill end of life situation has been chosen for all the plants as it ensures a relatively higher estimate of eco-point indicators and, moreover, recycling is neither predictable nor guaranteed and it will only be performed after the project life of 20 years.

Overall life cycle inventories of 50 MW horizontal axis onshore, offshore and vertical axis wind farms are highlighted in Table 1 for the aforementioned turbines.

3. Results and discussion

3.1. Comparison between HAWT onshore and offshore farm

It is very important to determine how the impact values of tower, foundation and ancillary components differ in HAWT onshore and offshore farms. Accordingly, the LCA results of this section highlight the same. As evident in Fig. 2, the foundation and ancillary eco-point values of HAWT offshore are much higher than HAWT onshore one. Total, damage and individual impact eco-profiles are sorted sequentially from left to right in 'damage and impact categories' axis of Fig. 2. Within the damage categories, HH maintains the highest kilo eco-point (kPt) whereas, within the individual impact categories, RI emission comes up with the highest eco-imprint in most sub-assemblies. RI emission basically happens due to the presence of steel and cast iron. The remaining processes are also important contributors. Impact category RI is an important constituent of damage category HH which causes it to be of higher value. The other impact categories with their base material and process contributors have been discussed in detail in Subsection 3.4. Other major impact contributors include E, M, FF, C and CC, etc. Here 1 kPt eco-impact value indicates the LCA impact caused by 1000 average European persons over the time period of 1 year.

As vivid from Table 1, an onshore tower needs almost 75% more steel than its offshore counterpart. Quantities of other materials used in the turbine design do not vary significantly. Hence, an onshore tower carries 70% more kPt in comparison to offshore one. In turn, offshore foundation comes up with 1667.78 kPt which is around 3.7 times of what the onshore foundation integrant parts display. The reason behind this lies in material information where an onshore tower uses only 22% steel of its offshore complement. Other than these, great difference of kPt values lies in ancillary sub-assemblies. Ancillary components include parts and items aside from turbine structure that are necessary to distribute the generated power to the national grid. It is evident from Fig. 2 that HAWT offshore ancillaries exhibit around four times more kPt than HAWT onshore turbine. Reasoning behind this again lies in additional inventory of high voltage transformer and its platform.

Next, life cycle damage comparisons of all sub-assemblies of HAWT onshore and offshore are featured in Fig. 3. Nacelle and rotor of both turbines exhibit almost equal eco-profiles as there is no significant inventory diversity between these sub-assemblies. Nacelle maintains highest kPts out of all and, hence, carries most deteriorating impacts, largely surpassing other sub-assemblies by distant difference. Next, large impact carrying subassemblies are: offshore foundation, onshore tower, onshore foundation and offshore tower, sequentially. It is revealed from Fig. 3 that a large impact carrying foundation comes with a low impact carrying tower and vice versa. Conversely, rotor eco-point value is less for both turbines due to lower material consumption. Overall, the HAWT onshore and offshore farm emanate 3649, 4937 kPts, respectively of impact based on 'single score' definition.

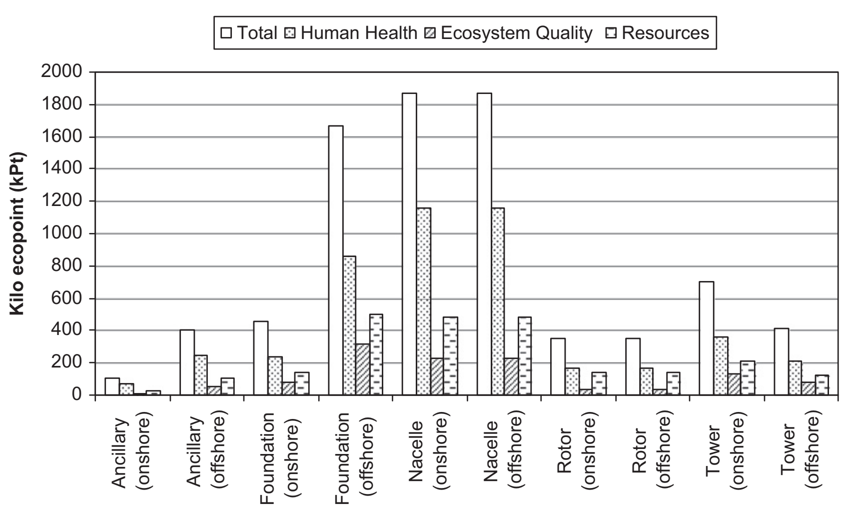

Fig. 3. LCA assessment of all HAWT onshore and offshore sub-assemblies (FU=50 MW).

3.2. Comparison among HAWT onshore, HAWT offshore and VAWT farm based on unit electricity generation

This section demonstrates the compartmentalized life cycle damage and individual impact comparisons between HAWT and VAWT farms based on unit electricity generation (FU=1 kWh). As evident from Fig. 4, in all damage and most of the impact categories (except FF, R, RO, and OL), VAWT farm appears to be environmentally superior to HAWT ones with lower eco-point (Pt) representation; followed by HAWT offshore and HAWT onshore. Eco-profile of each unit electricity generation stands at 0.000719 eco-point (Pt) in VAWT farm while for HAWT offshore and onshore, it increases to 0.001105, 0.001225 Pt, respectively. Overall farm scale eco-point values stand at 1569.01, 3649.14 and 4937.10 kPt for VAWT, HAWT onshore and HAWT offshore farm, respectively.

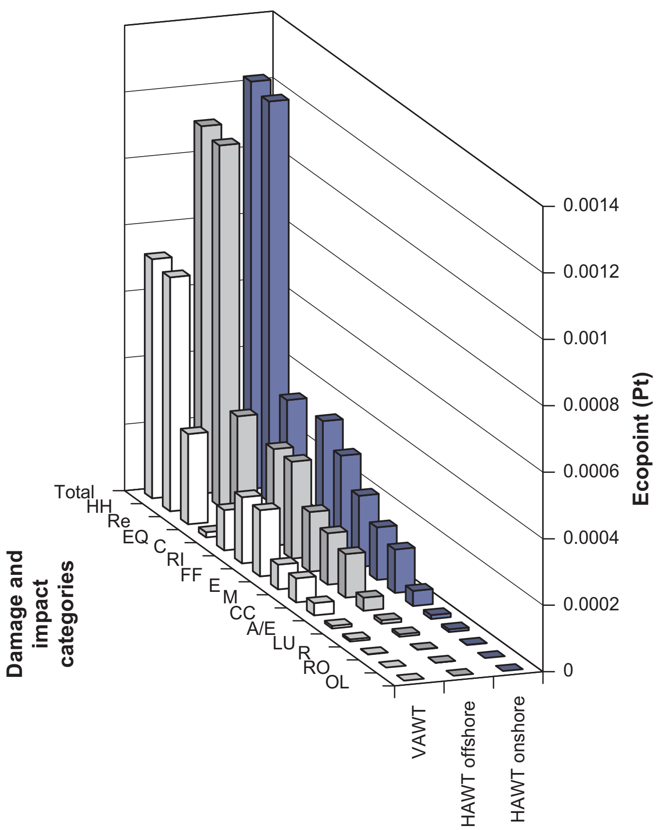

Fig. 4. LCA impact and damage assessment of wind farms (FU=1 kWh).

The onshore and offshore farm HH damage values are 1.72 and 1.54 times of VAWT farm values as revealed in Fig. 4. Similarly, EQ onshore and offshore values are 1.27, 1.14 times that of VAWT. Similar trend is noticed for Re damage. These results are major findings for VAWT farm as these establish it as being the most environment friendly wind farm within all categories. VAWT technology, in addition, offers lesser weight, simpler foundation and less maintenance cost. Besides, its power co-efficient can be greatly enhanced by introducing drag reducing airfoils. With all these merits coupled with a low imperative ecopoint (kPt), vertical axis turbine can be an alternative green electricity source of commercial scale in the coming future. Lastly, within HAWT farms, HAWT offshore technology proves its dominance over the other based on both life cycle eco-imprint and energy intensity perspective. This is mainly because of higher capacity factor of offshore farm. As mentioned in previous sections, the capacity factor of HAWT offshore farm is 50% more than its onshore counterpart. However, if capacity factor stands the same for both farms (34%), the offshore farm will have much more impact than onshore farm for per unit electricity generation.

3.3. New material and process with low LCA imprint

As mentioned in previous sections, the present LCA study, at its very core, endeavors on proposing new materials and process routes that will eventually diminish life cycle eco-impact values without compromising the structural needs and functional requirements. Hence, the materials which are used in larger quantity in wind farms have been sorted out on priority basis. For this, a cut-off criterion of the materials with minimum 1% consumption (by weight) is used to explore the most impact and damage contributing ones (see Fig. 5). Later the materials are arranged sequentially in terms of their life cycle impact. As shown in Fig. 5, 'copper, at regional storage' Ecoinvent process which comprises all life cycle processes starting from material extraction to transportation to regional copper storage exposes most adverse effect to the surroundings with distant difference amongst all the materials.

Total impact, HH and EQ damage assessment value of 1 kg copper process attends to be 1.82, 2.94 and 3.19 times of

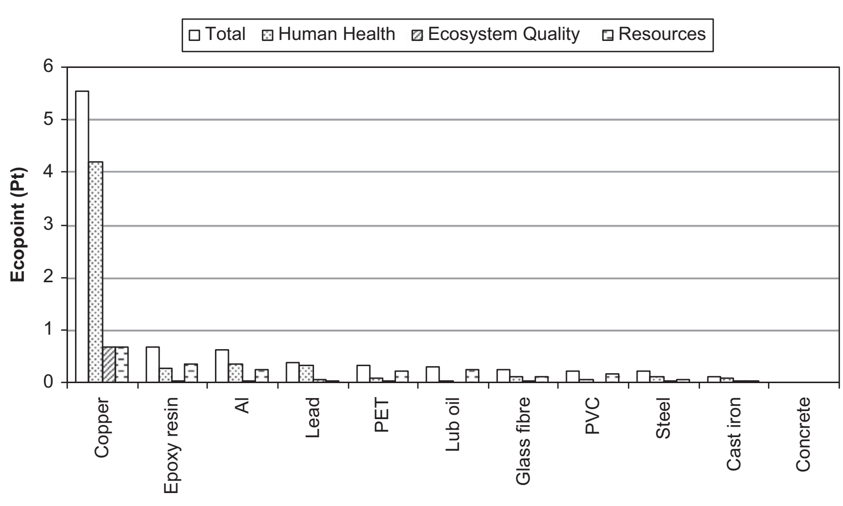

Fig. 5. Life cycle damage assessment of Ecoinvent process (FU=1 kg).

combined respective impact and damage assessment values of all other materials consumed at least 1% by weight in these farms. Steel is the most dominantly used material in all three farms. Nevertheless, in comparison to steel, copper imposes 27.45 times total life cycle impact. Next, environmental impact intensive materials are epoxy resin, aluminum and lead, sequentially, with impact values of 3.28, 3.04 and 1.92 times of steel. It is to be stressed that lead is quite carcinogenic and its usage should be eliminated as far as possible, especially in all the electrical solder joints. Glass fiber and steel material exhibit comparable eco-indicator points. Cast iron is better than glass fiber reinforced polymer (GFRP) composites and alloy steel and, obviously, concrete is the best within all materials under study, as highlighted in Fig. 5. Concrete is 43 times and 1979 times life cycle impact savvy as compared to cast iron and copper, respectively.

When analyzed based on per unit weight basis, overall farm scale impact findings are demonstrated in Fig. 6, which again manifests the deteriorating effect of copper, though it is used at much lower quantity in all three farms (see Table 1). Comparatively, 'concrete, normal, at plant' process leaves very negligible impact in HAWT onshore farm.

To reduce total wind farm impact, it appears of absolute importance to replace copper material with other alternative materials. As listed in Table 1, HAWT onshore and offshore farms experience usage of copper in cable, generator and transformer, whereas in VAWT farm, it is only used in cable. In generator and transformer, copper is fundamentally used as winding material. In all these components, copper is chosen due to its high electrical conductivity and low price. Better substitutes of copper can be explored from appropriate material selection database like

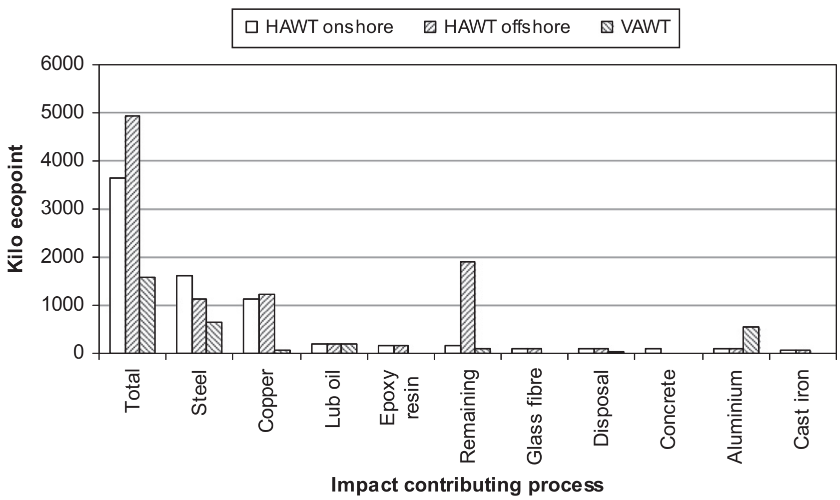

Fig. 6. Wind farm LCA processes by life cycle impact (FU=50 MW, cut-off point=1%).

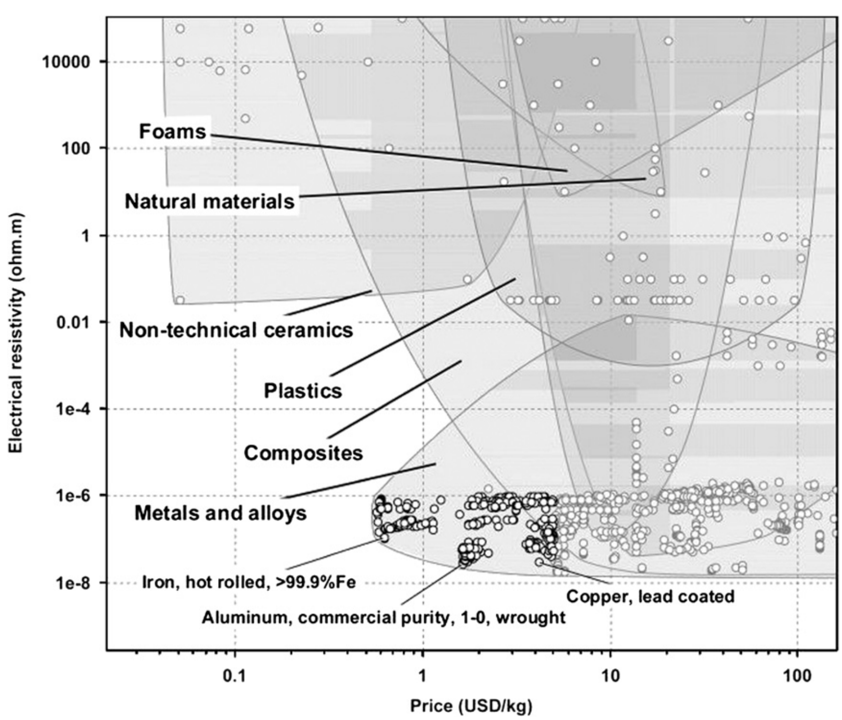

Fig. 7. Material selection chart in terms of electrical resistivity versus unit price to find substitute material for copper in generator windings.

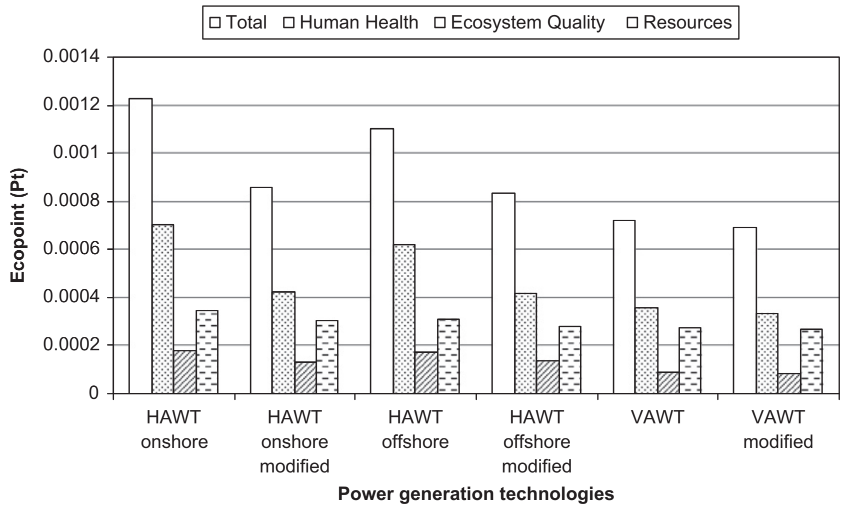

Fig. 8. LCA impact comparison between existing and modified design (FU=1 kWh).

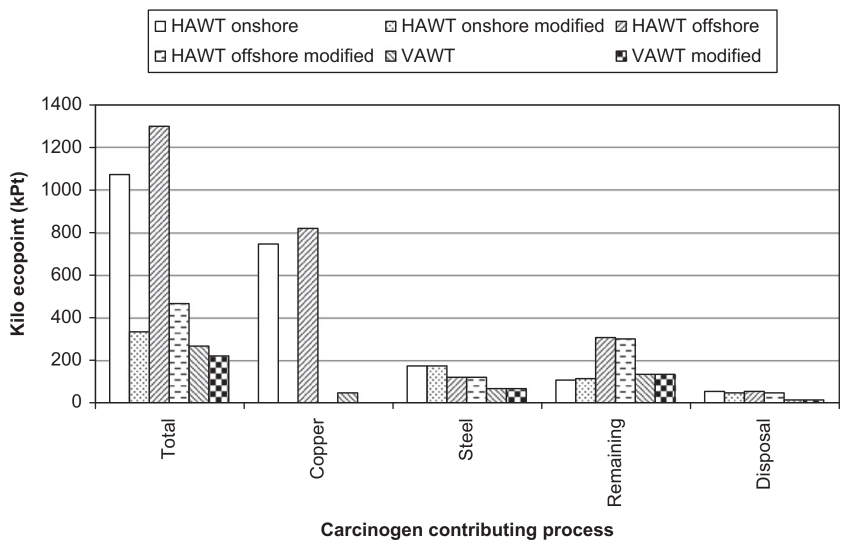

Fig. 9. LCA processes by carcinogen impact contribution (FU=50 MW).

Cambridge Engineering Selector (CES) [30], as shown in Fig. 7. For this, a limit based search criterion is implemented in CES whose lower and upper bound limits are suggested as:

$$\rho_{elr} \leq 3 \times 10^{-8}\ \Omega\,\mathrm{m} \tag{1}$$

$$C_m \leq 5 \cdot \mathrm{USD/kg} \tag{2}$$

where ρ_{elr} and C_m indicate electrical resistivity and material cost per kg, respectively. Based on Eqs. (1) and (2), 'aluminum, commercial purity, 1-0 grade' appears as a substitute material. Its electrical resistivity and price are $2.7 \times 10^{-8}\ \Omega$ m, 1.65 USD/kg, respectively. In addition, its density is one-third of copper alloys [30]. So, simultaneous mass, cost and LCA impact minimization can be achieved by using this Al alloy. Its other durable characteristics include non-flammability, significant draw-ability, excellent behavior under the exposure to sun, fresh water and ocean environment, and excellent strength properties. With all such aspiring potentialities, aluminum can replace copper in this inventory.

Other replacements also can be ensured with introduction of low LCA impact based monolithic and sandwich composite blade design. Particularly, enhanced usage of sandwich structures comprising green composite facesheets and biofriendly core materials can improve the blade design from both structural and life cycle perspective. But because the LCA databases are still in their infancy with regards to impact categorization of diverse types of sandwich and composite materials, this substitution remains out of the scope of this paper.

Next, a concrete tower design compared to a presently used steel tower can greatly decrease the life cycle imprint in the expense of structural optimization, as highlighted in Fig. 6.

Fig. 8 demonstrates the life cycle impact reduction in all farms by replacing copper with aluminum which ensures almost 30%, 25% and 7% impact reduction in HAWT onshore modified, HAWT offshore modified and VAWT modified design, respectively, with their corresponding counterparts. This is to mention that in the current era when, worldwide, scientists are closely examining the ways to ensure an environment with more sustainability and lower eco-profiles, the reduction of LCA impact values in all sorts of future wind farms through newer generation green turbines will lead the way to the next dimension. This sort of LCA based eco-profile study should be, as accordingly, coupled with optimal material selection strategies for all structural designs for ensuring a sustainable earth.

3.4. LCA process contribution in overall farm scale

At this stage, the study focuses on overall farm scale impact contributing processes that carry individual process based LCA studies in both existing and modified designs. As depicted in Fig. 4, impact categories like R, RI, OL, A/E and LU turn out with minor ecopoints in all farms; hence, only the major adverse effect transporting impact categories are followed up in this concourse. Fig. 9 represents life cycle processes that intensely contribute to carcinogenic emission. Carcinogenic substances, in essence, are some cancer triggering substances that include dioxin, benzene, kepone, asbestos amongst many others. From figure it is vivid that 'copper, at regional storage' Ecoinvent process contributes maximum carcinogenic impacts in the existing design, followed by 'steel, low-alloyed, at plant' process. Total carcinogenic impact arises to be almost one third of all onshore and offshore wind farm eco-impacts whereas, in modified design, its contribution reduces to around one-seventh time in both onshore and offshore farms. Same phenomenon continues in VAWT. However, as copper amount is significantly lower in VAWT, steel leads the tally in current design.

Wind farms additionally emit significant RI substances. HAWT offshore issues 1302 kPts while onshore and VAWT farms emit 879, 434 kPts, respectively. Within the processes, steel contributes most followed by copper, epoxy resin and cast iron in existing designs. In offshore farm, remaining processes, altogether, exude large ecopoints; but, on individual level, they do not contribute 3% impact which is the cut-off point. Additionally, VAWT farm does not witness any consumption of epoxy resin or cast iron. Hence, equivalent ecopoint columns demonstrate zero kPt contribution (see Fig. 10). Comparatively, in modified designs, RI emission diminishes by around 10% in all plants due to lower copper usage.

Atmospheric green house gases (GHG) e.g. water vapors, CO_2, CH_4, NO_x and ozone layer absorb some part of solar thermal radiation that increases the global temperature and, ultimately, exerts climate change effect. As highlighted in Fig. 11, steel and aluminum based processes outperform the rests in all farms in climate change category. Rankwise other contributing processes include concrete, epoxy resin, glass fiber, disposal activity, etc. Copper does not contribute to climate change. Hence, replacement of copper does not bring any change in wind farm's impact on climate change.

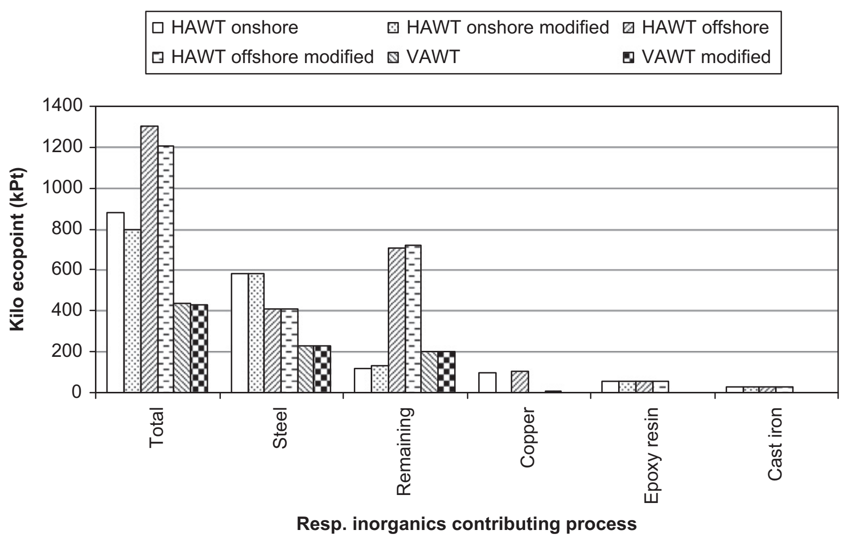

Fig. 10. LCA processes by respiratory inorganics impact contribution (FU = 50 MW).

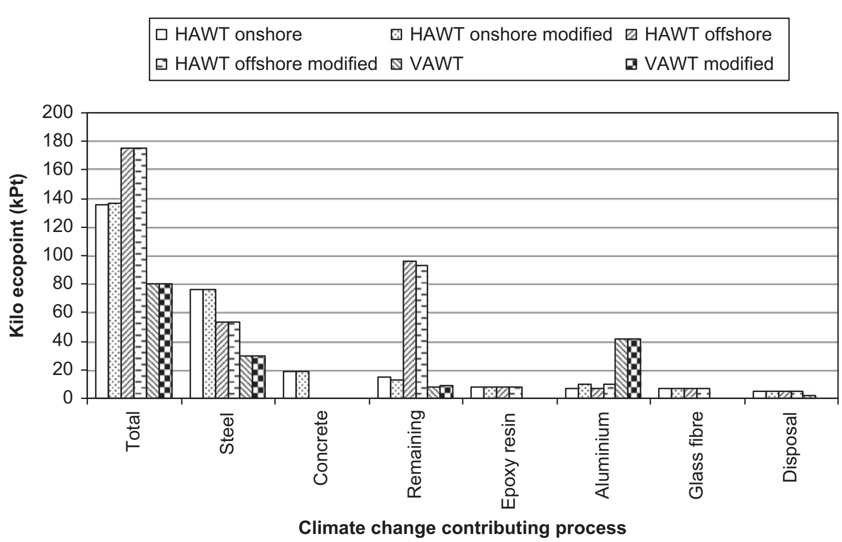

Fig. 11. LCA processes by climate change impact contribution (FU = 50 MW).

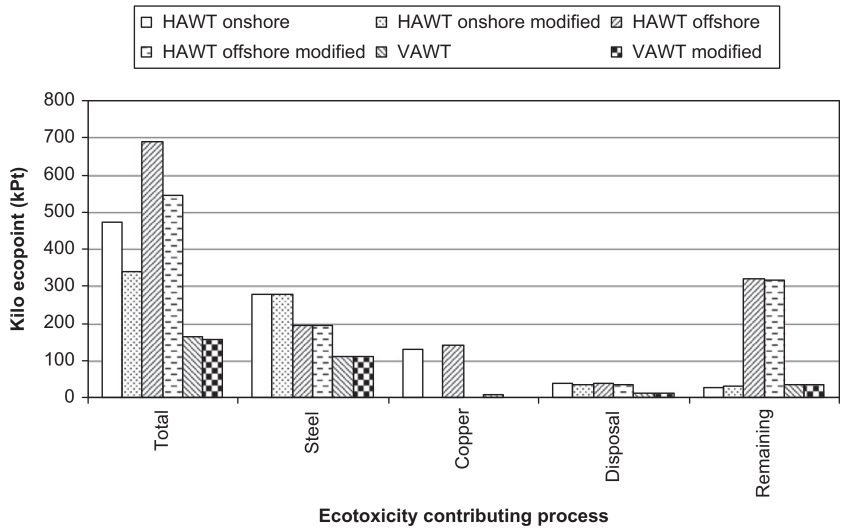

Fig. 12. LCA processes by Ecotoxicity impact contribution (FU=50 MW).

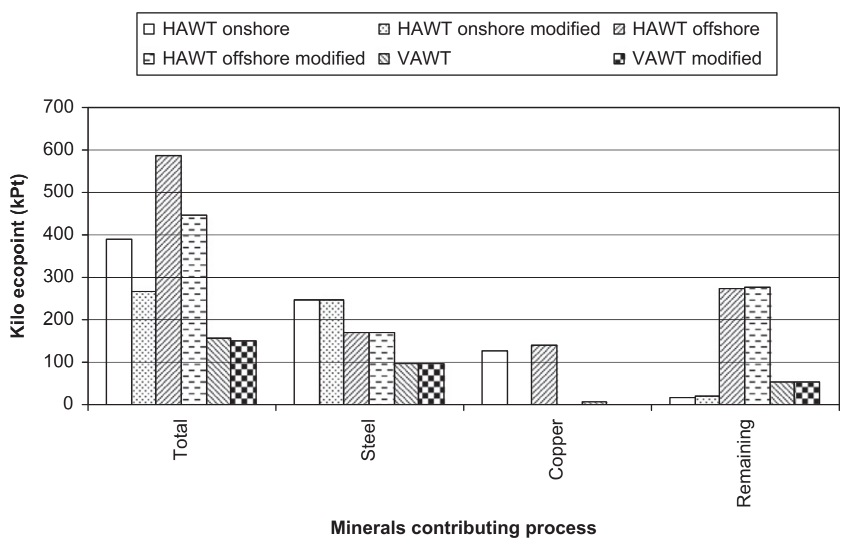

Fig. 13. LCA processes by minerals impact contribution (FU=50 MW).

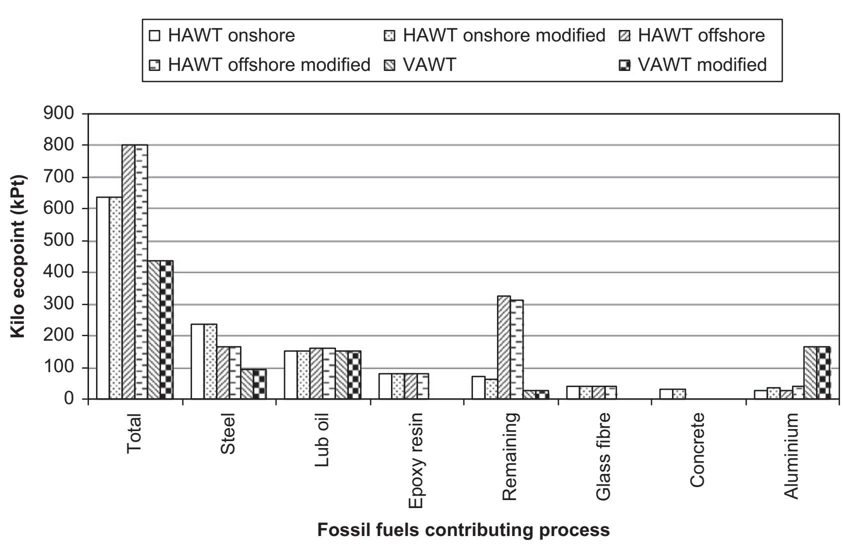

Fig. 14. LCA processes by fossil fuels impact contribution (FU=50 MW).

Table 2
Life cycle impact assessment of major power generation technologies (FU = 1 kWh) [27].

Impact category	Total	C	RO	RI	CC	R	OL	E	A/E	LU	M	FF
Oil	153.74	364.77	155.02	89.84	261.74	30.98	1,376,664.12	9234.38	336.88	114.59	5.67	556.88
Diesel	142.91	517.71	285.75	38.71	305.24	0.00	450.78	12,938.11	151.53	0.00	0.00	626.06
Natural gas	110.54	378.77	178.54	46.51	178.95	5.25	5032.57	271.79	94.00	2.42	**1.00**[a]	478.38
Coal	68.39	85.09	35.90	98.96	289.30	0.00	143.19	637.35	291.94	0.00	0.00	53.70
PV	13.47	1467.72	29.80	5.42	16.11	30.38	138,230.03	2923.66	11.40	10.36	51.87	22.86
Biomass	9.18	**1.00**[a]	16,253.51	11.10	12.45	0.00	**1.00**[a]	**1.00**[a]	55.98	0.00	0.00	1.39
Nuclear BWR	8.95	1347.47	3.31	4.05	2.85	2586.93	733,044.35	1326.06	3.41	3.44	6.71	2.87
Nuclear PWR	7.73	1254.00	2.90	3.58	1.43	1809.89	6230.51	1259.81	2.42	2.66	6.93	2.44
HAWT onshore	2.65	252.46	2.89	1.50	2.25	2.80	5462.47	1037.99	1.78	1.26	18.12	2.76
HAWT onshore modified	1.86	77.65	2.80	1.35	2.26	2.81	5473.94	750.81	1.59	1.15	12.35	2.76
HAWT offshore	2.39	203.46	2.48	1.48	1.94	2.61	4615.21	1015.19	1.54	1.21	18.17	2.31
HAWT offshore modified	1.80	72.98	2.41	1.37	1.94	2.61	4616.17	800.81	1.39	1.13	13.86	2.31
VAWT	1.55	85.11	2.56	1.01	1.82	3.51	6188.29	489.72	1.17	1.01	10.03	2.57
VAWT modified	1.49	10.68	2.55	**1.00**[a]	1.82	3.51	6189.27	466.00	1.15	**1.00**[a]	9.55	2.57
Hydro power	**1.00**[a]	12.29	**1.00**[a]	1.20	**1.00**[a]	**1.00**[a]	2693.69	182.62	**1.00**[a]	8.52	3.29	**1.00**[a]

[a] Indicates the minimum weighted value; other values indicate multiples of the minimum weighted value.

Next, in ecotoxicity emission category, steel and copper processes deliver major contributions. Total ecotoxicity emission of existing HAWT onshore, HAWT offshore and VAWT farm is equivalent to 471, 691, 162 kPts, respectively, as vivid in Fig. 12. Higher ecotoxicity emission means the wind farms possess substantial potentiality to destabilize the natural ecosystem, bio-diversity and bio-chemistry of living organisms. Replacing the copper materials hereby reduces the ecotoxicity imprint by almost 25% in onshore and offshore farm and 5% in VAWT farm.

Wind farms also significantly contribute in mineral and fossil fuel depletion categories. 'Steel, low alloyed' process bears the greatest impact in mineral followed by 'copper, at regional storage'. Other processes are not as transcendental as these ones. Within the three farms, VAWT one has the lowest contribution with total 157.92 kPts, as vivid from ecopoint columns of Fig. 13. In turn, in fossil fuel impact category, aluminum and lubricating oil also dispense major ecopoints other than steel process, as highlighted in Fig. 14. Next, distinguishing contribution comes from 'epoxy resin, liquid, at plant process' (80 kPt). Replacement of copper does not improve fossil fuel impact values; but mineral impacts reduce by around 30% in both onshore and offshore farm and almost 5% in VAWT farm.

3.5. *Life cycle impact of major power generation technologies*

Finally, the life cycle impact of all major power generation technologies is compared in Table 2. Ecoinvent per kWh power generation process data are used hereby for all technologies except wind power [27]. Modified wind turbine plants are included in the analysis in addition to the existing ones. Rankwise plant LCA impact sequences demonstrate that fossil fuel based technologies can never compete with wind turbine and other renewable technologies. Out of fossil fuel technologies, Ecoinvent oil based plant process emanates worst LCA impact followed by diesel, natural gas and coal based plant. Photovoltaic (PV), biomass and nuclear plants are sequentially better than the fossil fuel technologies. The best performance is obviously demonstrated by hydro-kinetic power technologies. Wind farms compete better with all plants except the hydro-kinetic ones. And, out of all wind farms, VAWT farm holds more promises chased by offshore HAWT and onshore HAWT farm. In kilo ecopoint (kPt) basis, VAWT farm issues 1.55 times impact of hydroelectric one which may even further reduce with an offshore VAWT technology because of higher capacity factor in offshore technology, as been vivid in case of onshore and offshore HAWT technologies. Overall per unit electricity generation eco-profile is presented in Table 2.

The overall eco-impact comparison of all these farms is highlighted in column 1 of Table 2 where every plant is sequentially arranged with the topmost value indicating that much times (153.74) of the lowest value. So an oil plant contributes almost 154 times eco-impact of the hydrokinetic plant to generate every 1 kWh of electricity. Within all the plants, the highest carcinogenic effect comes from PV plant, highest respiratory organics emission effect comes from biomass plant, highest respiratory inorganics emission effect comes from coal plant, highest climate change effect is caused by diesel plant, highest radiation effect is generated by nuclear plant, highest land usage, ozone layer depletion and acidification/eutrophication effects are caused by oil plant, highest ecotoxicity emission and fossil fuel effect are contributed from diesel plant, amongst many other findings. Within the two most leading renewable technologies (solar, onshore wind turbine), solar farm exhibits 5 times more impact of onshore wind farm which rises to almost 8.7 times in comparison to onshore VAWT farm for every kWh of electricity generation. In view of this, wind power is more clean, green and environment-friendly than solar PV power. Accordingly, wind power installation should be prioritized to combat various scenarios and environmental issues like fossil fuel depletion, global warming, climate change, ozone layer depletion, etc. It is also noteworthy to mention that wind power is simultaneously much cheaper than solar power. Specially, for many locations of the world, solar power is still not financially viable due to higher commissioning cost whereas the reverse is true for wind farms except the equatorial zones where wind speed hardly exceeds 3.5 m/s which is a major pre-requisite for higher wind power generation. More specifically, in higher latitudes ($>40^\circ$ north or $>40^\circ$ south), it is still a long journey for solar power to achieve the parity with existing fossil fuel based plants.

4. Conclusions

This article has compared the outcomes of LCA and LCIA of three multi megawatt wind farms in both horizontal and vertical configurations. Companion material selection methodology is focused consequently to ensure the impact reduction in the future *green turbines*. Though LCA researches are being conducted for last two decades, LCA guidelines are just standardized in the beginning of new millennium and in this stage these studies need to be streamlined with advanced impact savvy material selection

process as it is not pursued much with deserved attention. This study opens up avenues for low impact material selection process based on established impact assessment methodologies and future LCA studies are likely to follow the same course to accommodate and harmonize the respective inventories based on sustainable design guidelines and reduced life cycle eco-imprint principles. Eventually, the key contributions of this study can be documented as follows:

- The list of leading wind farm impact categories includes carcinogen, respiratory inorganics, ecotoxicity emission, and increase in extraction energy of minerals and fossil fuels. And, out of damage categories, 'human health' appears to be prominent in all three wind farms.
- Offshore horizontal wind farm exhibits higher impact values than onshore horizontal one. However, as its capacity factor is almost 50% more than onshore one, per unit electricity profile of HAWT offshore farm is more lucrative and eco-friendly than HAWT onshore.
- VAWT onshore farm performs the best within all farms with lowest ecopoint (Pt) values. This provides a significant edge for VAWT technology over the other wind turbine technologies. It is worth pointing out, at this stage, how an offshore VAWT farm, if designed, will emanate its life cycle eco-values.
- Within the LCI list, copper carries most significant impact that attends to be 1.82 times of combined respective impact values of all materials that are consumed more than 1% by weight in three wind farms. The study subsequently replaces copper with aluminum and eventually reduces overall LCA impacts by 30%, 25%, 7% for modified HAWT onshore, HAWT offshore and vertical axis farm, respectively.
- Finally, a comparison of all major renewable and non-renewable power generation sources reveals the wind farms as competing remarkably with all technologies except the hydro-kinetic ones.

A limitation in the study, nevertheless, lies in application of more advanced impact assessment methodology that may incorporate even more comprehensive impact categories. This area draws enhanced attention of researchers of this field.

Acknowledgments

A. Rashedi thanks the Energy Research Institute at NTU (ERI@N), Nanyang Technological University (NTU) for the financial support in the form of a Research Scholarship. Authors thank Dr. N Srikanth for many fruitful discussions on this work.

References

[1] Sayigh A. Worldwide progress in renewable energy. Renewable Energy, 2009, http://dx.doi.org/10.1016/j.renene.2008.12.025.
[2] Spiegel RJ, Kern Jr EC, Greenberg DL. Demonstration of the environmental and demand-side management benefits of grid-connected photovoltaic power systems. Solar Energy 1998;62(5):345–58.
[3] Al-Karaghouli A, Renne D, Kazmerski LL. Solar and wind opportunities for water desalination in the Arab regions. Renewable and Sustainable Energy Reviews 2009;13(9):2397–407.
[4] Rashedi A, Sridhar I, Tseng KJ. Multi-objective material selection for wind turbine blade and tower: Ashby's approach. Materials and Design 2012;37:521–32.
[5] Wikipedia. From website: 〈http://en.wikipedia.org〉; 2012.
[6] ISO 14040. Environmental management—life cycle assessment—principles and framework. Geneva: International Organisation for Standardisation; 2006.
[7] ISO 14044. Environmental management—life cycle assessment—requirements and guidelines. Geneva: International Organisation for Standardisation; 2006.
[8] Ardente F, Beccali M, Cellura M, Lo Brano V. Energy performances and life cycle assessment of an Italian wind farm. Renewable and Sustainable Energy Reviews 2008;12(1):200–17.
[9] Weinzettel J, Reenaas M, Solli C, Hertwich EG. Life cycle assessment of a floating offshore wind turbine. Renewable Energy 2009;34(3):742–7.
[10] Fleck B, Huot M. Comparative life-cycle assessment of a small wind turbine for residential off-grid use. Renewable Energy 2009;34(12):2688–96.
[11] Martinez E, Jimenez E, Blanco J, Sanz F. LCA sensitivity analysis of a multi-megawatt wind turbine. Applied Energy 2010;87(7):2293–303.
[12] Pre´ Consultants, Sima Pro 7.2.4 software. From website: 〈www.pre.nl〉; 2010.
[13] Wagner H, Tryfonidou R. Wind energy under the aspect of sustainability. Technical report; 2005.
[14] Kadlec EG, Grover RD. Economic analysis of Darrieus vertical-axis wind turbine systems for the generation of utility grid electrical power: volume III: point designs. Technical report; 1979.
[15] REpower 5M. From website: 〈http://www.repower.de/index.php?id=237&L=1〉; 2010.
[16] PRe´ Consultants. The Eco-indicator 99. A damage oriented method for life cycle impact assessment methodology report 2nd edition; April 2000.
[17] REpower press releases. From website: 〈http://www.repower.de/index.php?id=151&backPID=214&tt_news=253&L=1〉; September 2004.
[18] REpower press releases. From website: 〈http://www.repower.de/index.php?id=151&backPID=25&tt_news=194&L=1〉; July 2004.
[19] Goesswein J. Repower's offshore experience pushing the limits. Le Havre: REpower Official Presentation; April 2009.
[20] Seidel M. Jacket substructures for the REpower 5M wind turbine. In: Proceedings of European offshore wind conference; 2007.
[21] Seidel M, Mutius M, Steudel D. Design and load calculations for offshore foundations of a 5MW turbine. In: Proceedings of Deutsche Windenergie-Konferenz (DEWEK). Wilhelmshaven; 2004.
[22] Jonkman J, Butterfield S, Musial W, Scott G. Definition of a 5-MW reference wind turbine for offshore system development. Technical report; February 2009.
[23] Engels W, Obdam T, Savenije F. Current developments in wind. Technical report. Energy Centre of Netherlands (ECN), E-09-96; 2009.
[24] Environmental product declaration. ABB product guide: Generator AMG 0900. From website: 〈http://www05.abb.com/global/scot/scot234.nsf/veritydisplay/e87da12604e15ba4c125784f00380043/$file/epd_amg0900_en_revb.pdf〉; 2011.
[25] Environmental product declaration. ABB product guide: power transformer S-P-00054. Available online: 〈http://www05.abb.com/global/scot/scot292.nsf/veritydisplay/e7c381463152c60bc1256de900407090/$File/PT%20250%20MVA.pdf〉; 2011.
[26] Statistics Norway. Norwegian input output table. From website: 〈http://www.ssb.no/nr_en/input-output.html〉; 2000.
[27] Swiss Centre for Life Cycle Inventories. From website: 〈http://www.ecoinvent.ch〉; 2010.
[28] Rashedi A, Sridhar I, Tseng KJ. Life cycle assessment of a marine current turbine. In: Proceedings of the 3rd international conference on engineering and ICT (ICEI 2012). Melaka, Malaysia; 2012.
[29] Lapin EE. Darrieus wind-turbine performance and weight-scaling calculations. Final report; 1980.
[30] Granta design, CES EduPack 2010 software. From website: 〈www.grantadesign.com〉; 2010.